Reciprocating Engine Peer Review

23 April 2002
Cummins Inc.
Dave Bolis

- Cummins Overall Purpose
- Cummins DOE Program
- Work
- Summary

Overall Program Purpose

- Develop Advanced Natural Gas Engine Technologies for Enhanced Power Generation Products.
- Long-Term Objectives:
  - 50% BTE
  - 0.1 gm NO_x/bhp-hr
  - Competitive Life Cycle Costs.

Current Program Objectives

- Product Demonstration in 2005
- 44% Brake Thermal Efficiency
- $BSNO_x$ of 0.1 gm/bhp-hr
- Improve Customer Value
  - Maintain or Improve Durability, Reliability and Operating Cost.

Technical Challenges & Strategies

- Our Primary Path Includes; High Power Density, Leaner Combustion, and Improved Engine Subsystems Designs to Achieve:
  - Durable Ignition Systems
  - Faster & More Efficient Combustion
  - Combustion Sensing
  - Knock Control
  - Exhaust Energy Recovery
  - Friction Losses
  - NO_x Aftertreatment
  - High Temperature Material Capability

Cummins DOE ARES Program

Technical Challenges & Strategies

Cummins Technology Activities								Technical Challenges for 50% BTE & 0.1 gm NO_x/hp-hr	Customer Values				
Spark Ignition Evaluation	DPI	HPDI	Base Engine	Air Handling	Turbo-Compound	Alternator	Aftertreatment		Fuel Efficiency	Operating Cost	Durability & Reliability	Maintainability	Emissions, NO_x
+	+	+		+	-			Operation at High BMEP	+		-	-	
+	+	+						Durable Ignition Systems		+	+	+	
+	+	+		+	-			Rapid/Efficient Combustion	+				+
+		+						Combustion Sensing	+		+	+	+
		+						Knock Control	+		+		
				+	+		-	Exhaust Energy Recovery	+			-	
			+	+				Friction Losses	+		-		
					-		+	NO_x Aftertreatment		-		-	+
			+					High Temperature Material Capability			+	+	

Each Technical Challenges Typically Affect Several Customer Values
And Are Typically Addressed by Several of Our Activities

Major Partners & Roles

- **Oak Ridge National Lab** - Spark Ignition and Materials Improvements for High Power Density Operation
- **Colorado State University** - Diesel Pilot Experimentation for High Power Density & Efficient Combustion
- **Ricardo Inc** - Diesel Pilot Modeling for High Power Density & Efficient Combustion
- **Westport Innovations** - HPDI (High Pressure Direct Injection) Combustion for High Output & Efficient Combustion

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Tasks and Activities

Task 1 Technology Development

- **Spark Ignition Combustion System**
- **Diesel Pilot Ignition**
- **HPDI**
- **Air Handling**
- **Aftertreatment**
- **Base Engine**

Task 2 SubSystem Development

- Spark Ignition Combustion System
- Diesel Pilot Ignition
- HPDI
- Air Handling
- Aftertreatment
- Base Engine
- Turbocompound
- Alternator

Task 3 Prototype Engine Design Integration & Test

- Architecture Selection & Virtual Build
- Prototype Design Integration & Test
- Product Charter & Contract

Task 4 Production Design and Development

- Production Design
- Performance Development
- Alpha & Beta Builds & Development

Task 5 Customer Demonstration

- Customer Site Installation & Support
- Demonstration
- Final Report

Spark Ignition Evaluation

Objectives:

- Develop Fast & Efficient Combustion and Advanced Spark Ignition Hardware for High Power Density (20+ Bar BMEP)

Status:

- **Multiple spark plug designs identified w/potential longer life. First test w/std plug indicates life at 20bar BMEP short of requirements.**
- Miller cycle, for efficient combustion, synergistic with air handling system efficiency improvements. Early results indicate combustion OK.
- Development agreement reached with our supplier to pursue a producible piston based on our best to date fast burn combustion system.

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Spark Plug Life

Objectives:

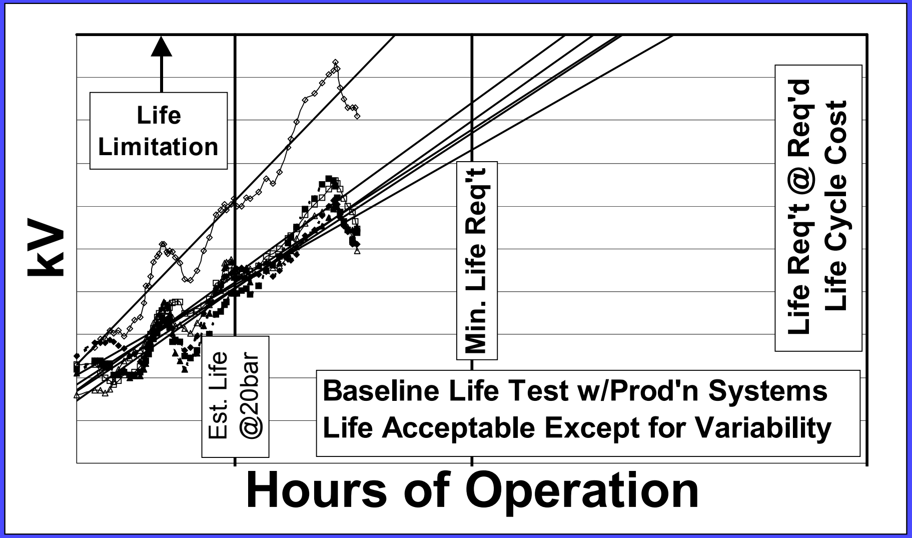
- Significantly Extend Life at High Power Density
- Build on Existing Technology
- Acceptable Life Cycle Costs

Status: Baselined Life @ 20bar & Measurement Approach, Advanced Plug Designs Available, 3 Engines Used for Test, Analysis Pre/Post Test Being Expanded

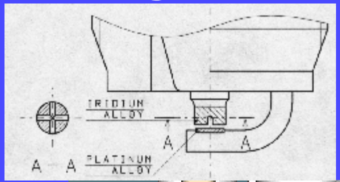
Benefits: Improves Existing Technology

Risks: Certainty of Being Cost Effective @ Required Ratings

Next Steps: Engine Tests & Plug Erosion Diagnostics Development



Entire Ignition System Being Studied for Improved Life:

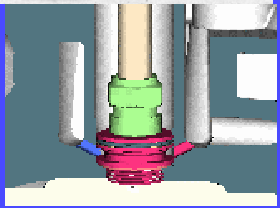


Materials; Ir+

Geometries

Electrical Supply

Engine Interface



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Diesel Pilot Ignition

Objectives:

•Develop a Diesel Pilot Ignition System for High Durability Ignition

•Demonstrate Performance, and Cost Effectiveness Against Alternatives

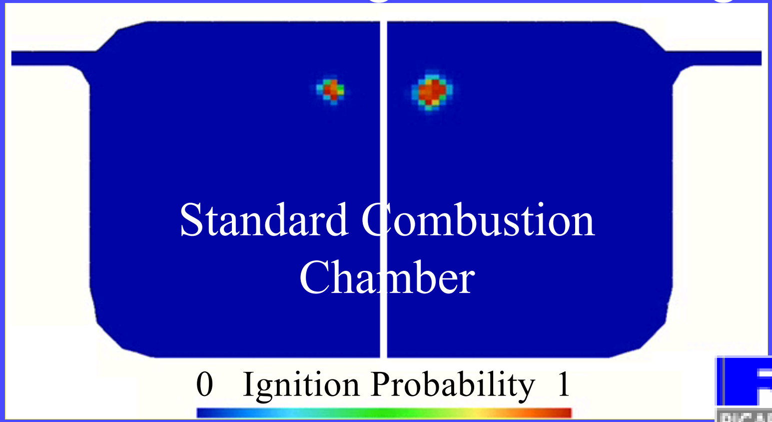
Status: Technical Requirements Supported by Modeling & Design Integration, Test Engine Ready, Literature & Patent Search Conducted

Benefits: Technology Aligns with long life technology (diesel engine)

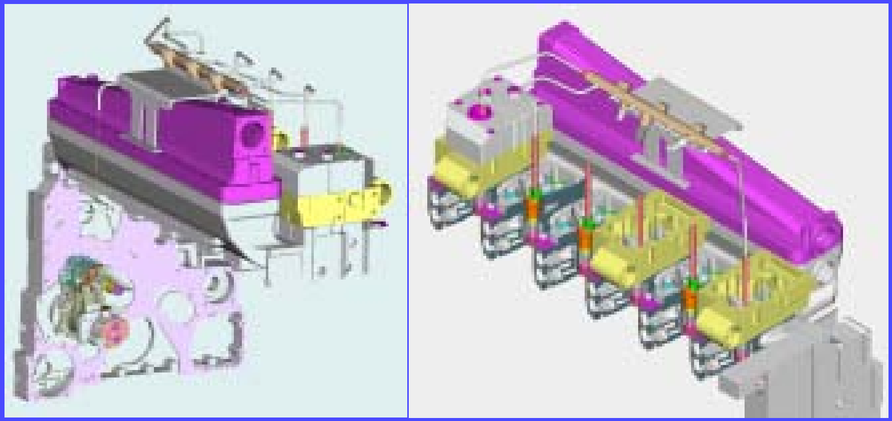
Risks: Time to prove Durability & Reliability Meet Expectations, Level of Emissions

Next Steps: Concept Engine Test Validation and Model Development

VECTIS Pilot Ignition Modeling



Fuel Pump and Accumulator Installation



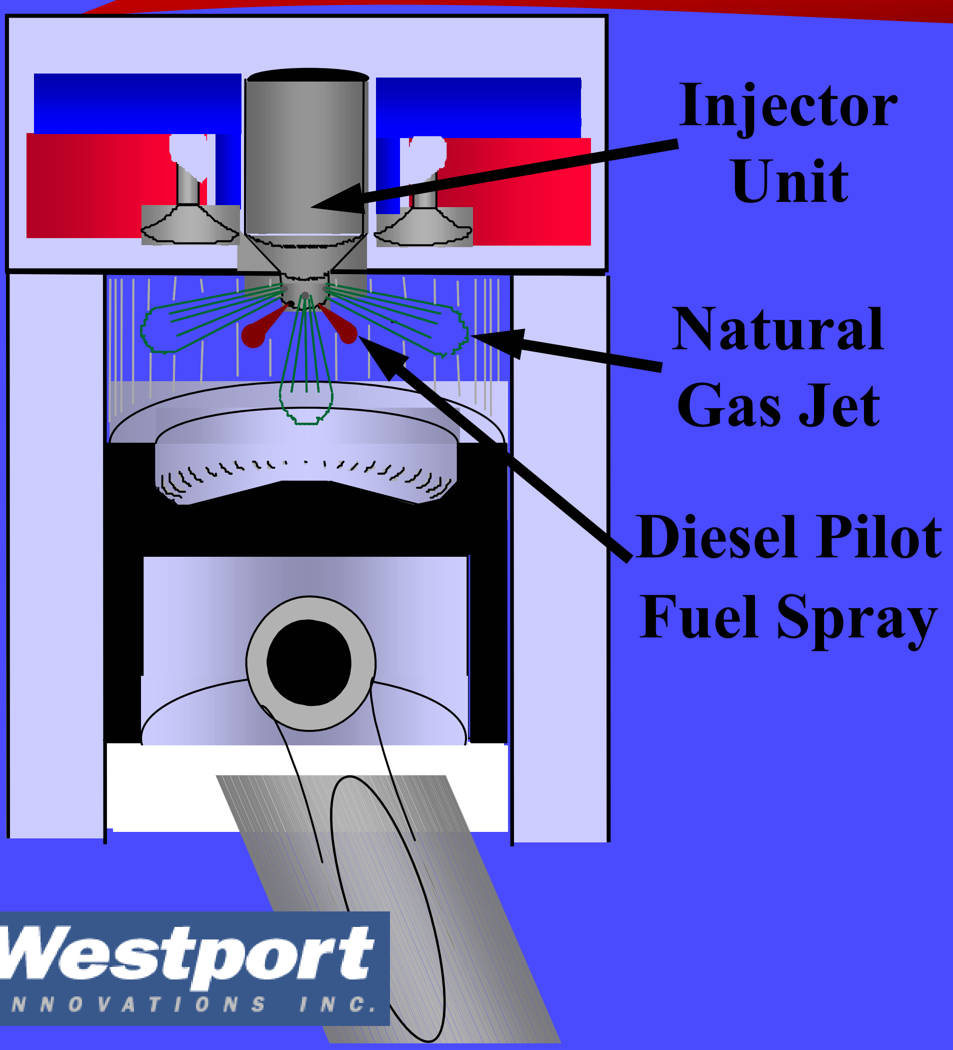
HPDI (High Pressure Direct Injection)

Objectives: Develop Fuel System for Improved Combustion and Reduced Parasitics

Status:

- 1 gm NO_x Achieved with Efficiency 5% Better than Spark Ignited.
  - The next generation fuel system and controls improved emissions, thermal efficiency and engine governing.
  - Controlling the compressor provides highest off-design efficiency.
- Combustion Sensing Design Concepts Developed and Prototype Testing Successful
- An Innovative Compressor Design Prototyped.

High Pressure Direct Injection



1) HPDI Diesel Pilot Auto Ignites Providing Ignition

2) HPDI Injects Natural Gas for Combustion & Power

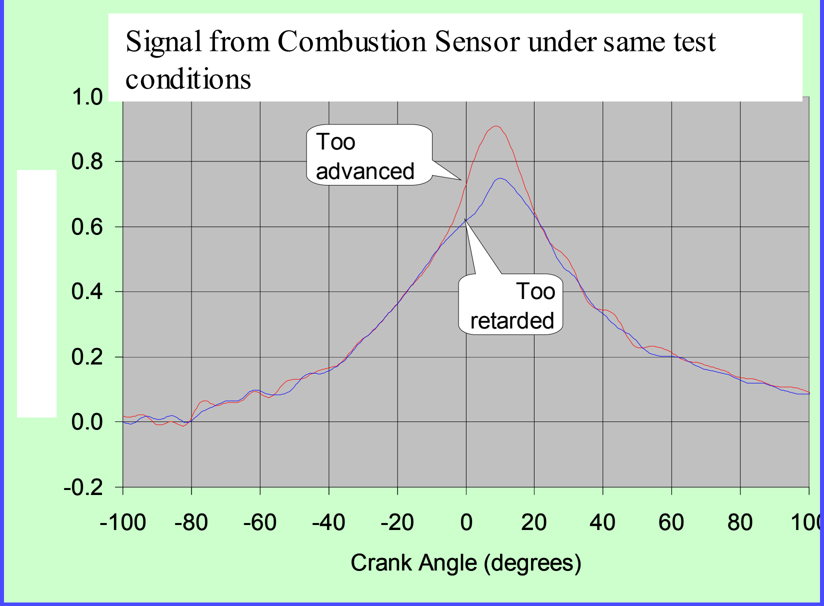
Combustion Sensor

Highlights:

- Significant progress on the algorithms and hardware required for Combustion sensing.
- Demonstrated Accuracy Required for 5% efficiency improvements
- Evaluation underway to select best sensor/supplier alternatives.

Next Steps:

- Finalize sensor design/supplier
- Development and durability



Air Handling

- Turbocharger matching shows that overall turbocharger efficiencies 1% point less than requirement for 2005.
- Further Intake Port development is needed to recover flow capacity loss with design for swirl (fast combustion).

Results & Accomplishments

Aftertreatement

- Technology for 0.1 gm NO_x appears feasible. Early performance is achieving 95+ % NO_x conversion.
- A preferred catalyst supplier chosen.

Market Study

- The multi-company market study started by EEA consultants.

Technology Progress Summary

Technology	Incremental Improvements		Target 2005 Improvements		Status
	BTE	NOx	BTE	NOx	
HPDI	2.0		2.0		**GREEN**
Air Handling	0.5		1.1		**GREEN**
Fast Burn	TBD		1.0		
Chamber	[0.1]		[0.5]		**YELLOW**
Swirl	[0.5]		[0.5]		**GREEN**
Miller			1.0		**GREEN**
Aftertreatment	TBD	95+%	-0.4	95%	**GREEN**

Numbers in [ ] are not additive with rest of numbers in each column

GREEN – Achieving Target w/Identified Path
YELLOW – Reaching Target In Question w/Available Metrics
RED – Target Not Met & Do Not Have Path to Achieve

FY 2002 Plans & Expectations

• Pilot Ignition Design Requirements	June 02
• Prove Next Generation HPDI Performance	August 02
• Design Concept for Low Parasitics	**October 02***
• Demonstrate Life Limits S.I. Systems	**November 02***
• Limits of Turbocharging System Optimization	**December 02***
• Demonstrate Fast Burn System Producibility	**January 03***
• Second Generation Diesel Pilot System Operational	April 03
• Turbocompound Application Design Viability	April 03
• Air Handling System Tradeoffs Defined	July 03

* Milestone Moved >4 Months Out From Original Plan

Project Risks

- Readiness for Improved Efficiency Product Launches with New Ignition/Combustion Approach(es)
- Cost Effective Exhaust Aftertreatment

Summary of Results

- HPDI System Achieved 5% Better BTE Than Current SI System
- Miller Cycle Gives Several Beneficial BTE Effects
- Spark Ignition Life Tests Underway w/Life Improvements Defined
- Diesel Pilot Design Progressing Toward 1st Demonstration June 02
- Combustion Sensor Prototype Successful
- Turbomachinery Close to Meeting 2005 Expectations
- Aftertreatment Capable of Required NO_x Reduction for 2005
- Have Confidence Half of Improvements Required to Reach 44% BTE Achievable, Complete Validation Expected Next Year
- Project Risks As Expected; Ignition/Combustion & Aftertreatment

Impact of Project on ARES Program

Cummins is Developing Technologies Towards DOE Goals

- 50% Fuel to Electric Conversion Efficiency Targeted with <0.1 g/hp-hr NO_x.
- Fuel Flexibility to Include Multiple Gases & Aggressive Fuels. The Current & New Technologies are Compatible w/Hydrogen.
- Cost of Power Requires Continuous Improvement for the Market, consistent with DOE's 10% Lower Cost of Power. This includes improving reliability and maintainability.

Technology Phased Into the Market by:

- Three major product introductions by 2010, First in 2005
- Expect Several Technologies Can Be Marketed Independently

Conclusion

- Cummins View of the Market Requirements Aligns Well with DOE
- Making Good Progress on Technology Development.
- Expect to be in Position to Define Phase 1 Engine Architecture by Late 2003